ISSN 1068-3739, Russian Meteorology and Hydrology, 2010, Vol. 35, No. 9, pp. 590–595. © Allerton Press, Inc., 2010.
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Influence of Horizontal Inhomogeneity on Albedo and Absorptivity of Snow Cover

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Received May 25, 2010

Abstract—The variations of albedo and absorptivity of the snow cover are considered caused by the presence of the snow roughness in the form of sastrugi. The numerical modeling is carried out within the framework of statistical approach based on the analytic averaging of the radiative transfer equation and statistically homogeneous model on the basis of Poisson flows of points at the straight lines. The estimates of the influence of 3D-effects of the rough surface are represented depending on optical and geometrical characteristics of sastrugi and on the illumination conditions. It is demonstrated that if the absorption by the snow particles is weak (the single scattering albedo $w = 0.9999$) the reflection of radiation by snow decreases by ~ 2–3% when the sastrugi appear. This effect is more significant in near infrared spectral region where w is below 0.99.

DOI: 10.3103/S1068373910090025

1. INTRODUCTION

The albedo A of snow and its absorptivity $P = 1 - A$ are among the major parameters determining the climatologic changes in the atmosphere–underlying surface system [7]. The effect of spatio-temporal variations of reflecting properties of the snow cover are the considerable variations of radiation budget both of separate territories covered with snow during the long period of time and of the globe as a whole [13]. Even relatively small snow albedo decrease may lead to the increase in the solar radiation absorbed by it [11] and, therefore, may influence considerably on the course of hydrological processes (for example, it may change the dates and the intensity of snow-melting processes). Besides, a high value of snow cover albedo is one of the reasons for the air temperature decrease in the lower troposphere [4].

The experimental data and numerical modeling results accumulated by now revealed that besides the shape and size of snow grains, the snow cover pollution, the direction of solar radiation incidence, etc., the albedo and the reflection coefficient depend on the surface roughness as well [5, 12]. To obtain the quantitative estimates of the influence of this factor, several models were developed [5, 6, 9]. In particular, in [5, 6], the roughness was modeled in the form of the array of idealized sastrugi (rectangular parallelepipeds) regularly situated on a smooth non-Lambert surface that enabled to reduce the differences between the results of modeling and in situ experiments (in particular, to decrease the peak in the scattering direction "forward" and to increase the peak in the scattering direction "backward"). However, the differences taking place till now indicate the necessity of further development of such models. In addition to the investigations dealing with the description of the influence of the roughness effect on the reflecting properties of snow, the statistical approach is proposed to be used. In this paper, a brief description of models and computation methods are given as well as the estimates of the roughness influence on the snow cover albedo obtained on their basis.

2. MODELS AND COMPUTATION METHODS

An available information on the underlying surface (US) containing a great number of macro-heterogeneities is insufficient for unambiguous determination of reflected radiation at the arbitrary point of the phase space of coordinates and directions. However, it is possible to make the conclusions important for practice on the realizations of ensemble averaged US heterogeneities, the characteristics of reflected radiation,

i.e., to reveal the interrelation between the statistical characteristics of the rough underlying surface and radiation and to analyze it.

One of the possible methods to realize the statistical approach is based on numerical or analytical averaging of stochastic radiative transfer equation. Although it was used for the first time to describe the radiation regime of mesoscale fractus cloudiness [2, 3], its application may be useful to develop the theory of radiation transfer at other optically macroheterogeneous scattering and absorbing mediums (choppy sea surface, mountain system with random distribution of heights and normals, etc.). It is proposed to use the model and methods given in [2] to estimate the roughness influence on the characteristics of solar radiation reflected from uneven snow cover.

The optical snow cover model taking account of roughness is specified in the layer $\Lambda = (0 \le z \le H)$ in the form of random scalar fields of attenuation coefficient $\sigma(\vec{r})\kappa(\vec{r})$, single scattering albedo $w(\vec{r})\kappa(\vec{r})$, and radiation scattering indicatrix $g(\vec{\omega}, \vec{\omega}', \vec{r})\kappa(\vec{r})$ where $\vec{r} = (x, y, z)$ is the radius-vector; $\vec{\omega}$ is the unit vector. The stochastic structure of the rough surface is described with a random indicated function

$$\kappa(\vec{r}) = \begin{cases} 1, & \vec{r} \in G, \\ 0, & \vec{r} \notin G, \end{cases}$$

where G is a random ensemble of points in the layer Λ where the snow is present.

Assuming that the interaction of the optical radiation with gas-aerosol atmosphere within the layer Λ is absent, the stochastic radiative transfer equation relative to the random intensity $I(\vec{r}, \vec{\omega})$ at the point $\vec{r}$ in direction $\vec{\omega}$ has the form

$$\vec{\omega}\nabla I(\vec{r}, \vec{\omega}) + \sigma(\vec{r})\kappa(\vec{r})I(\vec{r}, \vec{\omega}) = w(\vec{r})\sigma(\vec{r})\kappa(\vec{r})\int_{4\pi} \frac{g(\vec{\omega}, \vec{\omega}', z)}{2\pi} I(\vec{r}, \vec{\omega}')d\vec{\omega}'. \tag{1}$$

Boundary conditions for (1) correspond to the solar radiation flux I_0 coming ($\downarrow$) to the upper boundary of the layer $z = H$ in the direction $\vec{\omega}_{\text{Sun}}$ and to the radiation reflected ($\uparrow$) from the smooth underlying surface with reflection coefficient $\rho_{\text{surf}}(\vec{\omega}, \vec{\omega}')$:

$$\begin{gathered} I^{\downarrow}(z = H, \vec{\omega}) = I_0(\vec{\omega} - \vec{\omega}_{\text{Sun}}), \\ I^{\uparrow}(z = 0, \vec{\omega}) = \frac{1}{c}\int_{2\pi} \rho_{\text{surf}}(\vec{\omega}, \vec{\omega}')|c'|I^{\downarrow}(z = 0, \vec{\omega}')d\vec{\omega}'. \end{gathered} \tag{2}$$

The direction $\vec{\omega}_{\text{Sun}}$ is determined by the zenith ξ_{Sun} and azimuth φ_{Sun} angles of the Sun being counted off from the axes OZ and OX, respectively: $\vec{\omega}_{\text{Sun}} = (\xi_{\text{Sun}}, \varphi_{\text{Sun}})$.

The models on the basis of Poisson point ensembles in space and at the straight lines will be used as the models of the field $\kappa(\vec{r})$ [2]. The suggested Poisson models of the field $\kappa(\vec{r})$ are the mathematical ones because the construction of the physical model of $\kappa(\vec{r})$ is a very complex independent problem. Nevertheless, according to authors' opinion, the use of Poisson models to describe the snow cover roughness is rather reasonable in a number of cases.

In particular, the sastrugi, narrow and solid snow crests with a length up to several meters and with a height from several centimeters to 20–25 cm, as a rule, are formed in polar regions under influence of the prevalent wind direction [5, 10, 12]. As a first approximation, the sastrugi can be approximated by rectangular parallelepipeds with the random horizontal size and with the fixed height H and the model based on the Poisson point flows at the straight lines can be used to plot the spatial realization of the field $\kappa(\vec{r})$. To plot it at the plane $z = 0$ within the area $[-R_x, R_x] \times [-R_y, R_y]$, the random field $\kappa_1(x, y)$ is specified in the following way (Fig. 1):

—the Poisson point flows $\{x_i\}$ and $\{y_j\}$ with intensities A_x and A_y are plotted at axes OX and OY, where $A_x \sim 1/D_x$, $A_y \sim 1/D_y$, where D_x and D_y are the mean horizontal sizes of sastrugi;

—at every rectangle $[x_i, x_{i+1}] \times [y_j, y_{j+1}]$, the random field $\kappa(\vec{r}) = \kappa_1(x, y)$ possesses the value of unity (the presence of sastruga) with probability p and zero (the absence of sastruga) with probability $(1 - p)$. The values of indicated functions for every rectangle are chosen regardless of each other. The probability of sastrugi presence p is determined by the fraction of the area occupied by sastrugi C: $p = C$. The variable C (which is, per se, analogous to "cloud amount" term) will be hereinafter called the sastrugi density.

The field $\kappa(\vec{r})$ plotted by this way is statistically homogeneous and isotropic. If the optical characteristics are constant

$$\sigma(\vec{r}) = \sigma,\ w(\vec{r}) = w,\ g(\vec{\omega}, \vec{\omega}', \vec{r}) = g(\vec{\omega}, \vec{\omega}'),$$

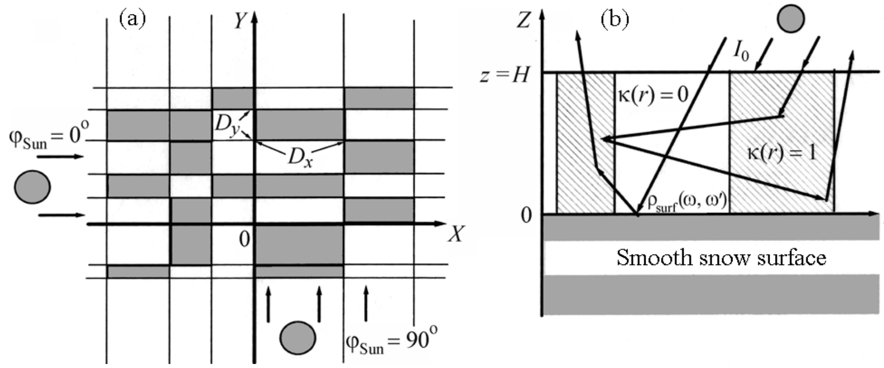

Fig. 1. The schematic model realization on the basis of Poisson point flows at the straight lines at the planes (a) *XOY* and (b) *YOZ*. The sastrugi situated at the horizontally homogeneous surface $z = 0$ are approximated by rectangular parallelepipeds with mean horizontal sizes D_x and D_y and constant height H.

then according to [2], the analytical averaging of the stochastic radiative transfer equation (1) can be made. The closed equation system for the first and second intensity moments is obtained for the derived equation relative to the average (for the set of realizations) intensity and the effective algorithms of its solution by means of Monte Carlo method (the method of closed equations) are developed. The detailed description of these algorithms to compute the average fluxes and intensities of solar radiation is given in [1, 2].

To carry out the computations, the set of input model parameters should be specified which characterize the optical and geometrical properties of the smooth snow cover, sastrugi system:

—attenuation coefficient σ, single scattering albedo w, radiation scattering indicatrix $g(\mu)$, $\mu = (\vec{\omega}, \vec{\omega}')$, or asymmetry factor of the snow forming the sastrugi $\overline{\mu}$;

—reflection coefficient from the flat horizontally homogeneous snow surface $\rho_{surf}(\vec{\omega}_{inc}, \vec{\omega}_{refl})$, where $\vec{\omega}_{inc}$ and $\vec{\omega}_{refl}$ characterize directions of incoming and reflected radiation;

—mean horizontal size of sastrugi D_x and D_y, height of sastrugi H;

—density of sastrugi C.

The proposed model broadens considerably the possibilities of investigation of 3D-effects on albedo and reflection coefficient of the rough snow surface because the input model parameters can be obtained directly from the observation data; the computation of reflected fluxes and intensity is carried out on the basis of effective algorithms of Monte Carlo method (there is no need to construct the realizations of the field $\kappa(\vec{r})$ when using the method of closed equations); the modeling of albedo and reflection coefficients is carried out taking account of all effects caused by the random geometry of the roughness: the incoming radiation flux can enter and the nonscattered and diffusion radiation can leave through lateral (nonhorizontal) surfaces limiting certain elements of uneven US; the incoming radiation may be shielded by surrounding sastrugi; the radiation interaction of certain roughness elements is observed, i.e., the radiation leaving through the lateral surface can be repeatedly scattered by surrounding sastrugi [2].

It should be noted that unlike the model used in [5], in this model the sastrugi are approximated by parallelepipeds with random horizontal size; besides, the effects of re-reflection between certain sastrugi are taken into account when computing the albedo and reflection coefficient and the shading of smooth underlying surface by sastrugi is described more correctly.

3. THE RESULTS OF NUMERICAL MODELING OF THE ROUGH SNOW SURFACE ALBEDO

The interaction of solar radiation with molecule-aerosol atmosphere is not taken into account during the computations given below that enables to reveal the “clear” 3D-effects of uneven snow surface. The use of such approximation is reasonable when analyzing the snow cover albedo measurements in the polar regions where the aerosol thickness of atmosphere is small.

3.1. Input Parameters

Since the radiation measurements are not always accompanied by the experiments during which the set of input parameters needed for computations can be obtained, the typical values of optical and geometrical

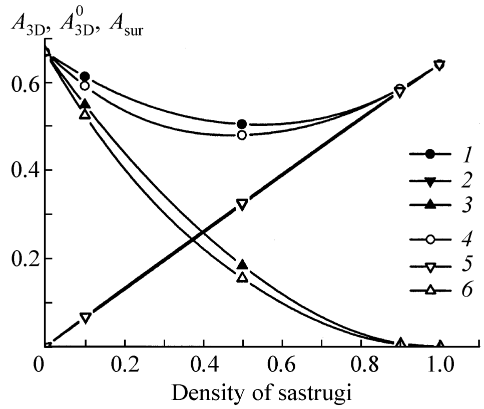

Fig. 2. (*1*, *4*) The albedo of the smooth snow surface, sastrugi system A_{3D} and its components (*2*, *5*) A^0_{3D} and (*3*, *6*) A_{sur} at $\xi_{Sun} = 75°$ and $w = 0.98$. (*1–3*) $\varphi_{Sun} = 0°$; (*4–6*) $\varphi_{Sun} = 90°$.

characteristics are specified as a rule. The numerical modeling is carried out at the following values of input parameters:

—$\sigma = 1$ mm^{-1}; $0.98 \le w \le 1$; $g(\mu)$ corresponds to the radiation scattering indicatrix [8] for the particles in the form of fractals with effective size of 50 μm; the asymmetry factor $\overline{\mu} = 0.76$;

—smooth underlying surface on which the sastrugi are situated is approximated by the semi-infinite layer; the optical characteristics of US and sastrugi (w, $g(\mu)$) are identical; the modeling of $\rho_{surf}(\vec{\omega}_{fall}, \vec{\omega}_{refl})$, is based on the numerical solution of nonlinear integral equation of Ambartsumyan [8];

—mean sizes of sastrugi along the directions of OX and OY axes are: $D_x = 10$ m, $D_y = 1$ m, $H = 10$ cm (for example, in [12] $D_y/D_x = 0.1$, $\gamma = 0.1$). Taking account of the influence of azimuth angle between the direction of sastrugi elongation (OX axis) and the direction of sunbeam incidence φ_{Sun} is carried out due to the variation of φ_{Sun}: $\varphi_{Sun} = 90°$ and $\varphi_{Sun} = 0°$ correspond to the situations when the azimuth angle of the Sun is perpendicular or parallel to the direction of sastrugi elongation, respectively (Fig. 1a).

The computations were carried out at zenith angles of the Sun $\xi_{Sun} \ge 60°$ which are typical of the polar regions of the globe.

3.2. The Influence of 3D-effects on the Snow Albedo

Investigating the influence of 3D-effects of the rough snow cover let us compare the albedo of horizontally homogeneous semi-infinite layer of snow (A_{flat}) and the albedo of the smooth snow surface, sastrugi system (A_{3D}). The latter variable is the sum of two components: $A_{3D} = A^0_{3D} + A_{sur}$, where A^0_{3D} is the albedo of the layer Λ computed assuming that the reflection from the surface $z = 0$ is absent and A_{sur} is determined by the contribution of photons which experienced at least one reflection from the smooth snow surface during the distribution process. Let us consider the factors influencing the formation of A_{sur} and A^0_{3D} (Fig. 2).

The value of A_{sur} is determined by the fractions of nonscattered and diffusion radiation which reached the surface $z = 0$. The corresponding fraction of the direct radiation decreases when the sastrugi are present as compared with the smooth surface and decreases still more due to the shading effect if the density of sastrugi C is fixed. For example, for the parameters mentioned in the heading of Fig. 2 at $C_0 > 0.7$, the direct radiation does not reach the surface $z = 0$ at all and A_{sur} is formed under influence of the diffusion radiation only due to the reflection from shaded areas as well. Besides, if the scattering is nonconservative, the photons experienced the collisions within the sastrugi before the interaction with smooth surface and a part of photons reflected from $z = 0$ can be absorbed within the sastrugi. Therefore, one can expect that the value of A_{sur} decreases with the increase in the density of sastrugi.

At the same time, the component A^0_{3D} is a steadily increasing function of the density of sastrugi. If the illumination conditions are fixed, the increase in A^0_{3D} with the increase in C is caused by the increase in the scattered radiation fraction, on average, and at large values of C when the distance between sastrugi decreases, on average, the radiation interaction effects considerably (the latter is caused by the fact that the part of radiation leaving through the lateral surfaces can be repeatedly scattered by adjacent sastrugi [2]).

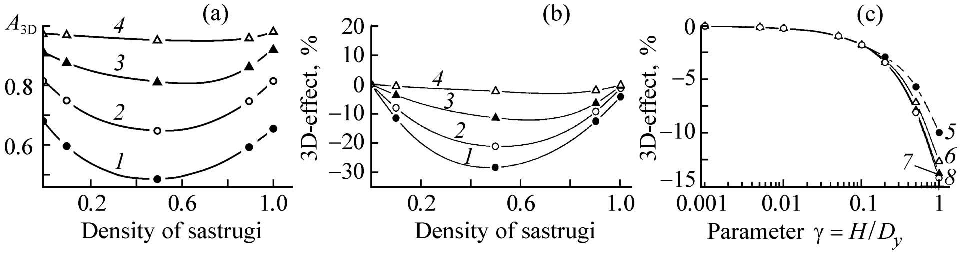

Fig. 3. The dependence of (a) albedo and 3D-effects of the rough snow surface on (b) the density of sastrugi and (c) parameter γ at various values of the single scattering albedo w and illumination conditions. (*1*) $w = 0.98$; (*2*) $w = 0.995$; (*3*) $w = 0.999$; (*4*) $w = 0.9999$; (*5*) $\varphi_{Sun} = 0°$; (*6*) $\varphi_{Sun} = 30°$; (*7*) $\varphi_{Sun} = 60°$; (*8*) $\varphi_{Sun} = 90°$; (a, b) $\xi_{Sun} = 75°$, $\varphi_{Sun} = 90°$; (c) $\xi_{Sun} = 60°$, $w = 0.9999$.

Thus, if the density of sastrugi is small ($C \sim 0.1$–0.2) the main contribution to A_{3D} belongs to the radiation reflected from the smooth surface. At large values of C ($C > 0.7$–0.8), the albedo forms mainly due to the processes of absorption and scattering observed directly within the layer Λ.

As a whole, the results of numerical modeling revealed that

—the albedo of the rough snow cover surface is less than the albedo of the flat layer:

$$A_{3D}(C > 0) \le A_{flat} = A_{3D}(C = 0);$$

—the albedo of the smooth snow surface, sastrugi system has the minimum being reached at the medium density of sastrugi C ($C \sim 0.5$);

—at the small and medium values of C, the inequality $A_{3D}(\varphi_{Sun} = 90°) \le A_{3D}(\varphi_{Sun} = 0°)$ takes place which is partly the effect of the decrease in the US areas illuminated by the nonscattered solar radiation.

It should be also noted that if the scattering is conservative (the scattering within the sastrugi and the reflection from US are indiscernible) the equality $A_{3D}(C = 1) = A_{flat}$ should be satisfied. However, since A_{flat} corresponds to the albedo of semi-infinite flat layer and $A_{3D}(C = 1)$ is computed at the optical thickness $\tau = \sigma H$, the values of A_{3D} and A_{flat} can slightly differ and $A_{3D}(C = 1) < A_{flat}$.

To describe quantitatively the influence of 3D-effects on the mean albedo A_{3D} as compared with the albedo of the flat semi-infinite layer A_{flat}, we use the variable

$$\Delta_{3D} = \frac{A_{3D} - A_{flat}}{A_{flat}} \times 100\%.$$

The detailed dependence of A_{3D} and Δ_{3D} on single scattering snow albedo at illumination conditions when 3D-effects are the most significant ($\varphi_{Sun} = 90°$) is given in Figs. 3a and 3b. It should be noted that if the snow absorptivity is small ($w = 0.9999$) the formation of sastrugi results in the decrease of A_{3D} by not more than 0.02–0.03 and $|\Delta_{3D}|$ amounts to less than 2–3%. If w decreases ($w = 0.98$) the influence of the roughness increases and $|\Delta_{3D}|$ reaches ~30% at the medium cloud amount.

The results represented in Fig. 3c demonstrate how considerable is the dependence of 3D-effects on the geometrical structure of the sastrugi field characterized by the parameter $\gamma = H/D_y$. Since the given computations are carried out for the mean values of the density $C = 0.5$ the obtained values of $|\Delta_{3D}|$ can be considered as the maximum ones if other parameters are fixed. It should be noted that the coefficient of light attenuation remained constant during the cited computations, i.e., the parameter γ increase (if D_y value is fixed) means the increase in the optical thickness of sastrugi as well.

If the snow absorptivity is weak ($w = 0.9999$) the increase in the geometrical thickness of sastrugi leads to the decrease in the albedo of smooth snow surface which does not exceed 10–15% even at the values of parameter $\gamma = 1$ unusual for the Southern Hemisphere depending on the orientation of sastrugi relative to the Sun. These results are harmonized with the results of the computations made by O'Rawe obtained at $\xi_{Sun} = 60°$ and represented in [12]. If the snow absorptivity increases, the change of A_{3D} relative to A_{flat} increases considerably: thus, if $w = 0.98$ even at weakly pronounced surface roughness ($\gamma = 0.01$) $|\Delta_{3D}|$ amounts to ~15% and if $\gamma = 1$ the deviation of $|\Delta_{3D}|$ increases up to ~35–45% depending on φ_{Sun}.

4. CONCLUSION

The snow cover albedo variations caused by the presence of the snow roughness are investigated by the example of sastrugi. To describe the influence of sastrugi being typical of the polar regions the statistical approach is used enabling to reveal the dependence between the mean (for a set of realizations) albedo and the mean characteristics of sastrugi [2]. The use of statistically homogeneous model on the basis of Poisson point flows at the straight lines and the supposition on the constancy of optical snow characteristics enable to use the effective methods of the computation of radiation characteristics by means of Monte Carlo method based on analytical averaging of the stochastic radiative transfer equation.

One of the main conclusions of this work is the revelation of the fact that the snow cover roughness (for example, sastrugi) can considerably decrease the snow cover albedo. It is especially clearly pronounced in near IR range where the albedo of snow grains is close to 0.98 and in some cases it is less than this value (for large crystals). The increase in the absorptivity of the rough surface caused by the albedo decrease influences considerably the heat regime of the snow and the melting processes. It should be noted that the influence of 3D-effects within the visible range where the single scattering albedo is close to the unit is insignificant.

Since the knowledge of spectrum-angle characteristics of reflected radiation is necessary for the determination of snow cover parameters using the methods of remote sensing, the proposed approach is planned to be used to estimate the snow roughness influence on the reflection coefficients of the snow surface.

ACKNOWLEDGMENTS

The work was partly supported by the Russian Foundation for Basic Research (grant 09-05-00963) and by the Foundation of the European Space Agency (Snow Radiance project).

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